SUMMARY

A workshop was held at General Atomics from September 11–14, 1995 to discuss the β limit in long pulse discharges. The workshop was organized by S. Jardin (PPPL) and T. Taylor (GA). Local arrangements were made by S. Kobayashi, D. Brummage, and A.D. Turnbull. Papers were selected by a committee consisting of S. Jardin (PPPL), M. Mauel (Columbia University), O. Gruber (MPI), R. Yoshino (JAERI), L. Zakharov (PPPL), and A.D. Turnbull (GA). The workshop was attended by 72 people. These are listed in Appendix A. The agenda is listed in Appendix B. The final announcement sent to all participants is given in Appendix C.

The workshop focused on addressing two general topics:

(i) <u>The impact of q_0 <1 (m/n = 1/1) on the stability limit at high beta:</u>

- Beta limit experiments in long pulse discharges.
- Experimental results which indicate the effect of q<1 on the beta limit.
- MHD modes at the beta limit with q_0 <1, and a comparison with those when q_0>1.
- Experimental, theoretical and numerical results on the role of the m/m = 1/1 mode on setting the beta limit when q_0 <1.

(ii) <u>The effect of toroidal rotation on the stability limit:</u>

- Theory and experimental results for locked modes.
- The impact of plasma rotation on locked modes, especially experimental results involving slowly rotating rf heated plasmas.
- The effect of sheared rotation on plasma stability, both theory and experiment.
- The influence of a resistive wall on stability.

These two topics correspond to two URGENT ITER R&D tasks, items 6.2 and 6.5 on the R&D list.

The talks were organized according to their relevance to these two main topics but with those talks focussed directly on experimental β limits separated out and slated for the first morning session. A discussion session was held on the fourth day. This was

organized so as to directly address the above topics. Specifically, four separate working groups were charged with providing summaries of the workshop presentations on the following four questions:

(i) What are the β limits in long pulse discharges?

(ii) What is the status of our understanding of the role of locked modes on the β limit in long pulse discharges?

(iii) What is the status of our understanding of the role of resistive wall stabilization of ideal kink modes?

(iv) What is the significant difference if any, in the β limits in discharges with $q_0 < 1$ and with $q_0 > 1$?

Summaries were compiled by the chairman of the respective working groups. These summaries comprise the basis of the present report. Each section in the following is the workshop consensus on the four specific questions given above.

I. LONG PULSE β LIMITS

O. Gruber (MPI) and D. Montiicello (PPPL)

A. EXPERIMENTAL OBSERVATIONS

Experimental data from "ITER β-limit demonstration discharges" was presented from JET, JT-60U, DIII–D, ASDEX Upgrade and COMPASS-D. These are summarized in Tables I and II. Results from TFTR (circular cross section) are also included in these tables. The achieved β values are for both stationary and transient discharges, revealing hard and soft limits. For all the cases presented in the tables the measured toroidal rotation velocities were below 105 m/s.

The results from JET, DIII–D and ASDEX Upgrade obtained for long pulse ELMy (Type I) H–mode plasmas with an ITER-like shape (β = 1.6–1.7, δ < 0.2), single-null divertor and q_{95} ~3 demonstrate reproducible operation with a normalized β_n between 2.4 and 3.8. The corresponding ITER quality factor, β_n/q_{95}, is between 0.8–1.2. These values are in the range of the ITER design which calls for β_n ~2.5 at q_{95} ~ 3. In ASDEX-Upgrade, the stationary phase lasts up to 3 seconds, which corresponds to 30 energy confinement times and one current diffusion time. One has to take into account, however, that the internal inductance l_i may be stationary during the high beta phase for the current and heating scenario envisaged in ITER. The ratio of T_e/T_i is ~ 1 and and q_0 values are around 1 in the JET, DIII–D, and ASDEX-U demonstration discharges.

The results from JT-60U (high β_p H–modes) and COMPASS-D showed a significantly reduced optimum β_n/q_{95} of 0.4–0.6. These discharges, however, differ from the above ITER demonstration discharges by the large differences between T_e and T_i, rather peaked pressure profiles, and a q_0 well above 1.

Higher β_n values can be achieved transiently by applying higher heating power, but the discharges end with a hard or soft beta limit. A dependence of β_n on q_{95} has been found on ASDEX-Upgrade, and the maximum value of β_n occurs around q_{95} ~ 3 to 3.5, with a soft limit above this value and a hard one below.

A significant sensitivity of both the stationary and transiently achieved β_n values to plasma shape has been found in DIII–D, ASDEX-Upgrade and Compass-D. It is found that the maximum β_n increases with elongation and triangularity. This supports the use of "advanced" scenario schemes.

A caveat of the presented results is the observed positive dependence of β_n with increasing plasma density (DIII–D) and decreasing B_T (DIII–D, TFTR) possibly implying a dependence on the collisionality v^*. This has to be clarified in future studies. The negative effect of a high B_T on β_n may also be due to operational problems such as lack of heating power, reduced beam penetration (change of pressure profile) or necessary higher current ramp rates (current penetration) needed to get higher plasma currents while keeping q fixed. Moreover "hard" collapses are more frequent in TFTR which may be due to $q_0 > 1$ or high n ballooning. We note that only JT-60U has sufficient heating power to drive ITER shaped discharges at 1.4 MA to the beta limit.

Generally, more peaked current density profiles show a higher β limit (in DIII–D for example: $\beta_n \sim 4l_i$), but for standard current profiles at $q_{95} \sim 3$ and $q_0 \sim 1$, there is little freedom to vary l_i and $l_i(3)$ is limited to $l_i(3) \sim 0.85$.

Resistive modes, possibly pressure driven, are seen to be the main cause of the observed β limits (see Table I). Pressure driven kinks near the edge (outside $q = 3$) play a role in the JET discharges, while ELMs are quoted only by JT-60U as being responsible for the very low beta limit ($\beta_n < 1.4$) in the ELMy H–mode. The hard β limit observed after long ELM free H–mode phases due to a "giant" ELM or a "combined ELM" (connected with a fall-back to the L–mode) should not be attributed to an ELM induced limit.

B. THEORETICAL ANALYSIS OF HIGH β_n DISCHARGES

Three of the machines that reported results on long pulse ITER like discharges presented theoretical analysis of some of these discharges. In particular, DIII–D presented two possible interpretations for their soft β limit scaling with square root of the density (see Table II). The first conjecture that was presented, posited that low density causes a modification of the current profile at the edge and that this current profile is unstable to low m/n resistive modes. These modes in turn cause enhanced transport and hence give a soft β limit. This explanation was supported by calculations which show that, indeed, the nonlinear three-dimensional steady state of the low density discharges had large islands present. The second interpretation, was that of the onset of neoclassical tearing modes. The scaling from a simple theory gave a scaling very close to that found experimentally.

It was shown that in JT60-U the long pulse, high β_p–*mode* discharges stringently obeyed ideal MHD stability limits. The optimized profiles are limited by pressure driven infernal modes. Experimentally, deviation from the optimized current and pressure profiles lead to lower β limits of the soft variety and it was conjectured that these limits may be due to low m/n resistive modes.

JET data also showed that ideal stability provided stringent limits on β, mostly limited by edge modes driven by a combination of edge current and edge pressure gradients. Evidence was also provided that optimized profiles could access the second region of stability. It was also pointed out that low m/n tearing modes have often been observed in JET β-limited discharges and it was suggested that the theoretical stability of these discharges should be investigated.

C. FUTURE WORK

The possible dependence of the β limit on the collisionality, n_e or B_T has to be clarified. This requires ITER similarity experiments to establish a dimensionless scaling of the β limit, which might depend on the limiting MHD instabilities.

The β limit experiments reported above used mainly NBI heating (the exception was the use of ECRH on COMPASS-D). This inevitably implies a correlation with beam heating (often non-central power deposition) and toroidal plasma rotation (< 105 m/s for the experiments in Table I). In addition, consideration must be given to the additional heating foreseen in ITER, central α heating, as well as wall stabilization mechanisms. Data for non-rotating RF heated plasmas are desirable, but only JET, JT60-U and COMPASS-D may have enough heating power. The reported data showed no obvious influence of the fast particle fraction. Profile control of the pressure p and current density j has not been used up to now and the desirable profiles will depend on the active instability. All teams should be encouraged to show that they can get successful ITER long pulse discharges with a disruptivity below 7%.

The theoretical effort is twofold, namely modeling of actual discharges and looking for optimal p and j profiles. The j profile has to be evaluated either from direct measurements (e.g. MSE and equilibrium fits) or from diffusion simulations including bootstrap and beam driven currents. Neoclassical effects on stability at low collisionality, due mostly to the bootstrap current, need to be investigated.

The experimental results presented here support previous findings that the transient β limits are always higher than the long pulse limits. The transient limits are obtained by overheating the plasma. The discharge ends in a disruptive event and the whole process takes place in too short a time for resistive modes to grow. This may be interpreted as saying that the high transient β discharges reach the ideal limit whereas the long pulse discharges reach the resistive limit.

Table I
Long Pulse β Limits in Major Experiments

ak	β_n	I_p[MA]	B_T[T]	q_{95}	β_n/q_{95}	shape	duration(s)	τ_E	τ_{skin}	remarks
	3.8	1	1.0	3.1	1.2	ITER	1.5	< 0.15	4–5	soft limit - edge mc Ph ↓
	3.8	1	1.4	4.7	0.8	κ = 1.7 δ = 0.4	< 1	0.14	4–5	at soft limit, Ph ↓
	3	1	1.4	4.7	0.6	κ = 1.7 δ = .04	6	0.12	4–5	limited by heating pc
J	2	2.3	4.4	3.2	0.6	κ = 1.7 δ = 0.1	1.5	0.3	> 10	elming, limited by carbon influx
	2.9	1	3	5.2	0.6	ITER	≤ 1	0.4	10	limited by carbon in
	2.4	2.2	4	3.2	0.7	ITER	hard limit	0.2	10	free boundary infer mode limited
	1.4									H–mode, elms (type limit beta
D	2.2	1.3	1.6	3.2	0.63	ITER	0.5	> 0.12	15	3/2 mode saturate
	3.0	1.3	1.6	3.2	0.94	ITER	1	0.085	15	no mode
	2.5	1.3	1.6	3.2	0.78	ITER	1.5	0.085	15	no modes
	3.5	0.7	0.8	3.8	0.9	κ = 1.9 δ = 0.4	1.5	0.038		only fishbones
-U	2.4	1	1.9	3	0.8	ITER	3	0.105	3	limited by 3/2, 2/ if raised heating pov
	2.9	0.8	1.5	3	1.0	ITER	transient	0.08	3	limited by low m/n te both hard and soft li
	3.2	0.6	1.5	4.2	1.0	κ = 1.7 δ = 0.3	0.4	0.065	3	limited by low m/n te
SS-D	1.7	0.15	1.1	3.6	0.4	κ = 1.6 δ = 0.1	0.3	0.007	1.5	2/1 mode cause soft l
	2.1	0.15	1.2	3.9	0.55	κ = 1.6 δ = 0.1	transient	0.01	3	2/1 mode cause hard
	2.3	0.15	1.2	3.9	0.6	κ = 1.6 δ = 0.4	transient	0.01	3	
	1.8	1.6	4.8	5.2	0.35	circular	0.6	0.14	15	end of NBI
	2.65	1.0	2.0	4.0	0.67	circular	transient	0.09	8	locked mode, slow col
	1.90	2.5	5.0	4.0	0.48	circular	transient	0.24	25	ballooning modes -

Table II
Status of Analysis and Modeling of Long Pulse Discharges

Tokamak	β_n	$H_{89\text{-}p}$	$\beta_{fast}/\beta_{total}$	T_e/T_i	$n/10^{19}$	p profile	$l_i(3)$	$q(0)$	Modeling
JET	3.8	> 2	0.4	1	3	triangular	0.85	0.7	YES
	3.8	2.2	0.3	1	3	triangular	0.85	0.7	
	3	< 2	0.3	1	3	triangular	0.85	0.7	
JT60-U	2	2.2	0.25	0.35	4	peaked	0.85	> 1	YES
	2.9	2.5	0.4	0.35	1.8	peaked	1.05	> 1	YES
	2.4	> 2	0.3	0.35	4	peaked	0.85	> 1	YES
	1.4	1.4				broad			
DIII–D	2.2	1.8	0.3	1	4	broad/triangular	0.85	1	YES
	3.0	1.8	0.2	1	6	broad/triangular	0.85	1	YES
	2.5	< 1.8	0.1	1	8.4	broad/triangular	0.85	1	
	3.5	1.5	0.25		5	broad/triangular	0.85	1	
ASDEX-U	2.4	1.8	< 0.1	1	8	triangular	0.8	< 1	YES
	2.9	> 1.8	< 0.1	1	8	triangular	0.8	< 1	
	3.2	1.8	< 0.1	1	8	triangular	0.8	< 1	
COMPASS-D	1.7	1.7		50	1.2	peaked	0.8	> 1	
	2.1	2.4		50	0.8	peaked	0.8	> 1	
	2.3	2.1		50	0.8	peaked	0.8	> 1	
TFTR	1.8	1.7	0.4	0.3	3.8	peaked	1.3	< 1	
	2.65	1.8	0.8	0.5	3	peaked	> 1	< 1	YES
	1.90	2.8	0.2	0.3	4.3	peaked	1.2	< 1	

II. LOCKED MODES — THEORY AND EXPERIMENT

R. Yoshino (JAERI) and T.C. Hender (CULHAM)

Two types of locked mode were identified

(i) Those which occur as a naturally unstable mode which grows in amplitude and locks due to resistive drag from eddy currents in the wall, and

(ii) Those which are driven by error fields and have no rotating phase.

These were discussed separately.

A. NATURALLY UNSTABLE LOCKED MODES

In present day large tokamaks the rotating modes (usually m=2,n=l) become large (~lO G) before they lock. In ITER, with its reduced rotation velocities, it is likely the modes will lock at lower relative amplitudes, so that locked modes will be the norm. There seems to be relatively good qualitative understanding of the locking process due to resistive wall drag.

There are direct problems from the *large amplitude* associated with locking for this type of mode. There are also some additional problems due to the fact that the mode is *locked*, namely:

(i) Hot spots on the divertor target
(ii) Impurity influxes
(iii) H–mode suppression (due to removal of shear flow)
(iv) Difficulty in measuring or diagnosing locked modes

No explicit R&D needs were identified for this class of locked modes

B. ERROR FIELD LOCKED MODES

Error field locked modes are undesirable for the same reasons as given above for naturally occurring locked modes. Also experimentally (in JET and DIII–D) it is observed that these locked modes almost always lead to disruptions.

In Ohmic plasmas the error field locked mode threshold is thought to be sufficiently well understood to make predictions for ITER of $\delta b\ (2,1)/B_t \sim 2\times10^{-5}$. There are however several areas which are less well understood:

(i) The reduced thresholds at high-β observed in DIII–D

(ii) Large amplification of the vacuum error field due to the plasma response (amplification ~50 in JET)

(iii) Ability of the error field to apply torque before any island is formed (in DIII–D magnetic braking experiments, the observed frequency reduction is ~5 times larger than predicted)

(iv) Possibility of other modes (e.g. 3,1 or 3.2) being important in ITER

The best way to prevent error field locked modes is to avoid them through careful machine design and construction. However, even with the most accurate construction error fields may still cause problems. Magnetic correction and momentum input therefore need to be considered. NBI is the most developed method for the momentum input. However the following effects should also be considered:

(i) Counter plasma rotation due to the diamagnetic drift (∇Pi)

(ii) Boundary conditions of the plasma rotation mainly determined by the charged exchange loss of particles

(iii) Co-plasma rotation is required for the bulk plasma to suppress impurity accumulation.

NB parameters (NB power and the acceleration voltage) should therefore be considered from the view point of the momentum input. Here, if a combination heating scheme with NBI and ICRF is planned, the effect of ICRF on the NB momentum input and on the momentum transport should be investigated.

However, for the suppression (or removal) of locked modes, local current profile control (CD at the O–point of the magnetic island) by ECCD is the most realistic for the following reasons:

(i) Momentum-input by NBI is unrealistic, because too large a momentum is required to remove the locked mode as a result of the amplification of the vacuum error field, and

(ii) EC heating of the O–point is unrealistic since too much power is required in an α-heated plasma.

C. FUTURE WORK

Theoretical and modeling work which needs to be done for error field locked modes was identified as:

(i) Locking thresholds near ideal instability boundaries need to be evaluated
(ii) Bootstrap amplification of formed islands needs to be investigated
(iii) Drag mechanisms for unpenetrated error fields need to be identified and evaluated
(iv) The V_ϕ profile from beams needs to be modeled
(v) The effect of velocity shear on toroidally and elliptically induced sidebands needs to be included in the theory and numerical modeling

The following experimental work which needs to be done was identified

(i) Document the locked mode threshold with and without momentum input (e.g. DIII–D and ASDEX-U)
(ii) Document the effect of ICRF on V_ϕ-control (e.g. ASDEX-U)
(iii) Demonstrate locked mode suppression by ECCD (e.g. ASDEX-U, COMPASS-D, and JFT-2M)

III. RESISTIVE WALL MODES: THEORY AND EXPERIMENT

A. Bondeson (Goteburg) and G.A. Navratil (Columbia University)

A. EXPERIMENTAL STATUS

Several key results were identified as being clearly established:

A resistive wall near a rotating plasma has allowed tokamaks to operate at up to 30% to 40% above the predicted ideal n=1 kink mode no-wall limit for many times. This has been demonstrated experimentally in carefully modeled equilibria on DIII–D, in a sequence of experimental equilibria with varying shape on PBX-M, and with a movable wall (although for only about l wall time constant) in HBT-EP. The advent of detailed MSE measurements of the intemal magnetic structure has allowed the range of uncertainty of the predictions of the ideal-MHD theory for modeled experimental equilibria to be reduced sufficiently that the observation of discharges whose β is 30% above the predictions of theory is statistically significant. It is also important to note, that no counter examples have been observed in plasmas without predicted wall stabilization effects which also exceed the ideal kink limits by these margins. These observations are in qualitative and rough quantitative agreement with MHD theory which predicts the possibility of the stabilization of both the ideal kink and resistive wall mode for plasma rotation at sufficiently high velocity with a resistive wall near the plasma boundary.

Excitation of the “Resistive Wall Mode” leads to plasma termination. In both PBX-M and DIII–D a slowly growing m = 3, n = 1 mode at the edge of the plasma was observed prior to discharge termination. In the case of DIII–D this 3/1 mode was observed to rotate relative to the resistive vacuum vessel wall at 25 Hz which is about 30% of the inverse of the 2 ms wall time constant as expected from the theory of an unstable resistive wall mode. In the case of PBX-M the wall time constant was closer to 40 ms and the rotation of the resistive wall mode predicted by the theory would be so slow that it is consistent with the quasi-static phase of the observed 3/1 mode.

Slowing down of the plasma rotation is the problem. In both DIII–D and PBX-M slowing of the plasma as the kink limit without a wall is exceeded preceeds the onset of the “resistive wall mode.” In DIII–D there are three possible sources of the slowed rotation:

(i) growth of large resistive modes in the plasma which drag on the resistive wall through eddy currents;

(ii) onset of ELMs; and
(iii) fast ion losses due to beam ion excited TAE modes.

In PBX-M a growing global mode was observed which was correlated with fast ion losses and could produce drag on the resistive wall through eddy currents.

Critical surfaces are at the plasma edge near q=2 and 3. In both PBX-M and DIII–D the onset of the “resistive wall mode” occured at the edge flux surfaces and the rotation velocity decreased in the range of 1 kHz at these surfaces at the time of onset of the slowly growing 3/1 resistive wall mode.

The critical rotation frequency seen experimentally ω_{crit}, is about 1% of the toroidal Alfvén frequency, ω_A. In both DIII–D and PBX-M, the critical rotation frequency is observed to be about 1 kHz which is 1% of the Alfvén frequency and a factor of 3 to 5 lower than the simple theory models predict.

B. THEORY STATUS

Toroidal code calculations have established that resistive walls and plasma rotation at a few % of the Alfvén speed can stabilize extemal kink modes for pressures up to 30% to 50% above the wall-at-infinity (Troyon) limit. Non-MHD dissipation mechanisms (such as ion Landau damping) may be important and appear to be necessary in order to explain the observed stabilization at low rotation speeds (about 0.01 v_A) in DIII–D.

Rotation and resistive walls can induce unstable resistive wall modes below the Troyon β limit, but for the small rotation speeds envisaged in ITER, this effect is too small to give an observable reduction of the β limit.

In principle, the resistive wall mode could be stabilized by trapped particle effects, but this will only work if the $\mathbf{E} \times \mathbf{B}$ rotation is small compared with the toroidal drift of the thermal particles (which will be of the order of 10–20 Hz in ITER).

C. OUTSTANDING QUESTIONS (THEORY AND EXPERIMENT)

The following questions were identified as unresolved and requiring further work:

(i) What is the scaling of ω_{crit} with ω_A and S?

Toroidal simulations indicate that ω_{crit} is some small fraction of ω_A (at fixed β and ω_s/ω_A), independent of the S-number. Certain analytic work in cylindrical geometry indicates that ω_{crit} scales as some resistive growth rate, e.g., $\omega_A S^{-3/5}$. The latter case would make it easy to obtain wall stabilization in ITER, whereas if ω_{crit} is S-independent, wall stabilization in ITER is expected to be marginal.

(ii) <u>Can tokamaks operate at 2 to 3 times the ideal n=1 kink mode limit without a wall through wall stahilization?</u>

The best results achieved in experiments are in the 30% to 40% range, while the most optimistic prediction of advanced tokamak equilibria employing negative central magnetic shear rely on wall stabilization for factors of 2 to 3 above the no-wall β limit. Enhancements of this magnitude have not yet been produced in any experiments.

(iii) <u>Can the slowing of plasma rotation observed in experiments be controlled to allow long pulse ($\tau >> \tau_E$) operation with β above the ideal n = 1 kink mode limit without a wall?</u>

In both PBX-M and DIII–D slowing of the plasma rotation was observed prior to the growth of the resistive wall mode to a level of about 1% of ω_A. It remains to be demonstrated that the identitied sources of drag or momentum input losses can be controlled and that the plasma rotation required for stability above the ideal-MHD no-wall limit can be maintained for long pulses.

(iv) <u>What is the dominant dissipation mechanism(s) for the resistive wall mode in a rotating plasma and what is the critical rotation velocity?</u>

Before a realistic prediction of the necessary rotation velocity can be made, it is necessary to find out what the major dissipation mechanism is, and also to find a sufficiently accurate model for it. In this respect, experiments show substantial wall stabilization at low rotation velocity ($\approx 0.01\ v_A$), whereas pure MHD computations indicate that several percent of the Alfvén speed are necessary. A likely candidate for strong non-MHD dissipation is ion Landau damping, which should be particularly effective at high q near the edge. This may bring theory in closer agreement with experiments.

D. FUTURE WORK

Several key experiments were considered that would significantly advance our understanding of resistive wall modes:

(i) Measure the scaling of ω_{crit}

— Scan the Alfvén speed (vary B_T and n_e).

— Scan q_a and explore selective braking using resonant external magnetic perturbations.

— Compare limiter versus diverted plasmas to understand how important the resonant surfaces between q_{95} and the separatrix are for dissipation of the resistive wall mode.

(ii) Explore plasmas with β_N approaching twice the no-wall kink β limit

The present studies on extending the performance of plasmas with negative central magnetic shear in TFTR and DIII–D should naturally provide this information as the radius of q_{min} is moved out to larger values and wall stabilization effects become more important.

(iii) Investigate the effects of wall structure and placement

Since ITER is presently considering a segmented wall design with complex eddy current paths, quantitative experiments on the role of the effective time constant and wall position can be carried out in HBT-EP and PBX-M.

(iv) Explore the possibility of active wall mode control

Schemes to use an active response of the wall to either simulate wall rotation, provide active feedback control, or induce plasma rotation have been proposed. These schemes can be tested on smaller exploratory experiments like HBT-EP and HIT to gain experience prior to testing on intermediate machines like DIII–D or PBX-M.

(v) Investigate electric field effects to modify the edge plasma rotation

Several techniques have been seen in experiments to modify the radial electric field near the plasma edge and change the plasma rotation profile. These include limiter biasing and LHCD or ECH with consequent fast electron losses.

Further theoretical work was also identified that will advance our present understanding:

(i) Resolve the scaling of ω_{crit} with S

Work is underway to understand the apparent discrepancy between toroidal computations, which indicate that ω_{crit} scales as ω_A, and analytical work, which indicates that in certain regimes the necessary rotation frequency scales as $\omega_A S^{-3/5}$. In this work, the toroidal stabilization of tearing modes (Glasser effect) should preferably be taken into account.

(ii) Determine the importance of ion Landau damping in stabilizing the resistive wall mode

Studies are being made of ion Landau damping in toroidal geometry, to give useful approximations to be fed into toroidal MHD stability codes. These studies indicate that, at low frequency, the ion Landau damping is weaker in a torus than in a cylinder, but it may nevertheless give strong dissipation near the plasma edge at high q. A completely satisfactory resolution of this issue may require a full toroidal drift-kinetic computation.

IV. β-LIMITS WITH $q_0 < 1$

L. Zakharov (PPPL) and E. Fredericksson (PPPL)

The conclusions reached on our present understanding of the effect of $q_0 < 1$ on the long pulse β limit can be summarized as follows.

(i) Regimes with $q_0 < 1$ do not impose significant limits on the global β and, despite existing uncertainties in the prediction of sawtooth behavior, may be acceptable for ITER.

(ii) Easy excitation of the m=1 mode (coupled with external and ballooning modes) near the β limit constitutes the major disadvantage of the $q_0 < 1$ regimes and should be carefully studied for ITER (including use of the more sophisticated numerical codes, such as MH3D).

(iii) With $q_0 < 1$, the most desirable stable regime for ITER implies frequent sawtooth oscillations (with a period less than the central confinement time), which prevent substantial buildup of the plasma pressure inside q=1.

(iv) Progress in the theory of the m=1 mode (kinetic effects, plasma rotation) as well as in understanding sawtooth stabilization has been made. A sawtooth triggering model has been proposed for ITER which predicts a considerable range in the sawtooth period. The model has to be calibrated against existing large experiments with necessary non-ideal effects included.

(v) Both theory and experiment (e.g. on JET) suggest that active control of the shear at the q=1 surface by local (LH or EC) current drive can be considered as a means to affect the period of sawtooth oscillations. In the case that further investigations show a high probability of “monster” sawteeth in ITER, this kind of active sawtooth control may be recommended for ITER.

Following is a more detailed discussion of the issues that were raised:

A. EXPERIMENTAL STATUS

Most of the experimental information on high β regimes with $q_0 < 1$ was from TFTR. On this machine, MHD activity at $q_0 < 1$ depends on β:

This activity can be summarized as follows:

(i) At low β (L–mode) TFTR exhibits ordinary sawtooth oscillations. An increase in β (transition to the supershot regime) makes the sawtooth period longer and finally stabilizes sawteeth.

(ii) While sawtooth oscillations are stabilized in the supershot phase, the m=1 mode is frequently observed in the plasma center in the form of a saturated mode, or as bursts of "fish-bone" oscillations. In contrast to sawtooth oscillations, this mode behaves like an "ideal" mode and does not produce magnetic islands.

(iii) "Ideal" m=1 activity, even when it is present, does not limit β in the plasma center. With increasing heating power, the pressure profile in the central zone of the discharge becomes well aligned with the high-n ballooning marginal profile. In these circumstances, the saturated m=1 mode facilitates excitation of ballooning modes near the q=1 surface, and they are observed in TFTR before the thermal quench.

(iv) Excitation of high-n ballooning modes may trigger a thermal quench which precedes both major and minor disruptions. It is observed that during the thermal quench, the m=1 mode coupled with an external mode (typically m=4) is amplified.

In DIII–D at high β, the sawtooth oscillations are often present in the discharge and major disruptions seem to be triggered by a particular sawtooth.

B. THEORY STATUS

Four different cases for sawteeth can be identified

(i) Complete stabilization,

(ii) Nonlinear stabilization,

(iii) Small sawteeth, and

(iv) Large sawteeth

Complete stabilization means not only no sawtooth crash but that the saturation amplitude is also negligible. This would mean either linearly stable or almost stable. Also $q_0 > 1$ can be included in this category as an example of complete stabilization.

Interaction of the saturated m=1 perturbation with ballooning modes as well as the thermal quench has been simulated numerically using the MH3D code. From this work, one, though not universally accepted, view is that if the saturation amplitude is large enough (nonlinear stabilization), the toroidally localized high-n mode will develop and a disruption will result. Only complete stabilization (e.g. $q_0 > 1$) or small sawteeth would prevent the disruption.

Sawtooth stabilization with increasing β has been explained using ω_* effects which are essential in TFTR due to the highly peaked density profile in the supershot regime. The criterion obtained distinguishes the sawtooth-stable operational space in all TFTR regimes including DD and DT plasma, NB and NB+RF heated discharges. This theory also predicts the experimentally observed saturated m=1 mode at high β. Thus, the theory clearly separates “sawtooth”- and “ideal”-like m=1 modes.

Despite progress made in understanding sawtooth stabilization and the relation of the m=1 mode to disruptions in TFTR, there is still a problem of how to interpret the ideal MHD stability calculations. At $q_0 < 1$, ideal MHD theory predicts a large growth rate for this mode (of the order of 1% to 3% of the inverse Alfvén time) in high-β regimes in both TFTR and DIII–D. Theoretical calculations of the β limits in this case use an empirical fact that the calculated growth rate exhibits a larger increase when approaching the experimentally observed critical β. Nevertheless, without completely resolving this issue, it is difficult to transfer results from the existing machines to ITER and to rely on theory for stability predictions for ITER.

The role of kinetic effects associated with the plasma trapped particles and with fast particles from the beams has been examined for TFTR. It was found that trapped particles can contribute significantly to the m=1 stability and diminish the discrepancy between stability theory and experiments. More comparisons should be made to obtain greater confidence in this result.

The theory of gyroscopic stabilization of the internal ideal m=1 mode has been developed for plasmas with rotation of the central core (due to unbalanced NB injection). The required rotation speed is observed in the DIII–D tokamak. While it is not likely that the effect of rotation is significant for balanced beams in TFTR, its contribution should be taken into account in comparing theory with experiment.

The first step in developing a sawtooth model for ITER has been made based on ideal MHD theory with kinetic and fast particles effects included. The theory relates triggering of the sawtooth crash with crossing of the stability boundary for the ideal m=1 mode. It assumes flattening of the q-profiles at the q=1 surface after the sawtooth crash. The resulting low shear at q=1 significantly amplifies the stabilization by kinetic effects and, thus, the ideal m=1 mode can be stable even at finite β. The period of oscillations in this theory is determined by relaxation of the q profile. Without kinetic effects, the model predicts a period of about 1 s whereas with trapped and fast particle effects included, the period becomes as large as 100 to 200 s ("monster" sawteeth).

Analysis of dimensionless parameters, relevant to sawtooth activity and to the m=1 mode at $q_0 < 1$, shows that ITER will be in a semi-collisionless regime which is not fully understood on the existing machines. The procedure of transferring data from present day tokamaks to ITER is still debatable. While TFTR data in high-temperature regimes seems to be well explained, it cannot be straightforwardly applied to ITER because of the significant difference in the density profiles in TFTR and ITER.

More theory should be developed in order to understand key issues like the period of sawtooth oscillations, radius of the q=1 surface and the q-profile inside the q < 1 radius. It was agreed that this theory has to include an accurate evaluation of the ideal m=1 contribution, effects of the trapped and fast particles, and the plasma rotation in the central core. In the singular layer, the necessary effects include ω_*, sheared rotation, resistivity, and the enhanced inertia due to trapped particles. Because predictions of the nonideal theory are much less certain than those of ideal model, massive comparison of the experimental data with the theory is necessary for development of a convincing theoretical model of the sawtooth and m=1 behavior. Such an extensive comparison is presently possible given the vast experimental data bases available on large tokamaks.

An important issue is the q- and pressure profiles that can be established self-consistently during sawtooth oscillations. The present theoretical understanding of the m=1 stability implies that the shear at the q=1 surface plays a destabilizing role for both resistive and ideal (with kinetic effect included) m=1 modes. There was experimental confirmation of this on JET, where active control of the shear at the q=1 radius by local LH current drive reduced the period of sawtooth oscillations when the shear was increased. This relationship between the period and the local shear should presumably prevent an uncontrollable drop of q_0 in ITER by excitation of more frequent sawtooth oscillations. Additional simulations should be done in order to quantify this feedback effect.

The buildup of the central pressure profile between sawtooth oscillations is controlled mainly by the plasma transport inside the q=1 surface. While considerable central β' is undesirable from a stability point of view, possibly triggering the disruption by a single sawtooth, hopes of flattening the pressure profile inside q=1 by Mercier modes seem at present to be unjustifiable. There is no evidence of such an effect in existing machines. Moreover, in TFTR, when violation of ballooning stability margins occurs in a restricted zone over the minor radius, ballooning modes (which potentially are more violent than Mercier modes) are frequently seen as quiet modes with no distinguishable effect on transport or plasma profiles.

Current drive can be used to control the sawtooth period (by modifying the shear at the q=1 surface) as well as to affect the radius of the q=1 surface. Numerical calculations assuming a β_N of about 3.5 in ITER show that a current drive fraction of about 10% of the total current in the middle of the minor radius (with the bootstrap current included) can completely eliminate the q=1 surface and raise q_0 above 1.

APPENDIX A
LIST OF PARTICIPANTS

F. Alladio	(Frascati)
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C. Bolton	(U.S. DOE)
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V. Chan	(GA)
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Z. Chang	(PPPL)
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J. Greene	(GA)
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M. Hughes	(Grumman)
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APPENDIX A
LIST OF PARTICIPANTS (Continued)

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S. Migliuolo	(MIT)
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APPENDIX A
LIST OF PARTICIPANTS (Continued)

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H. Wilson	(Culham)
R. Yoshino	(JAERI)
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L. Zakharov	(PPPL)
H. Zohm	(MPI)

APPENDIX B
MHD WORKSHOP AGENDA

Monday, September 11 — Day 1

Get Acquainted, Coffee		8:15 a.m.
Preliminary Remarks:		8:45 a.m.
D. Baldwin	Welcome from GA	5 min.
S. Mirnov	Welcome from ITER Expert Group Chairman	10 min.
T. Taylor	Workshop Logistics, Agenda, and Goals	15 min.
J. Wesley	ITER Design Status and MHD Stability R&D Needs	15 min.
Experimental Long Pulse Beta Limits—Session 1:		9:30 a.m.
T. Strait	Beta Limits in ITER-Like DIII–D Discharges	30+10
D. Monticello	Resistive MHD Analysis of DIII–D ITER-Like Discharges	20+10
	*** * * Break * * ***	
Y. Kamada	Beta Limits in JT-60U: Experimental Observations	30+10
S. Tokuda	Theoretical Interpretation of JT-60U Beta Limits	30+10
Experimental Long Pulse Beta Limits—Session 2:		1:30 p.m.
T. Hender	JET Beta-Limits	30+10
O. Gruber	MHD Operational Limits in ASDEX-Upgrade	30+10
H. Zohm	MHD Behavior Near Operational Limits in ASDEX Upgrade	30+10
	*** * * Break * * ***	
E. Frederickson	Beta-Limiting Scaling with Toroidal Field	30+10
D. Gates	The Effect of Current Profile Control on the Beta Limit in Compass-D	25+10
	*** * * Adjourn at 5:30 * * ***	

Tuesday, September 12 — Day 2

Resistive Wall Modes: Theory and Experiment		8:30 a.m.
A. Bondeson	Resistive Wall Stabilization	30+10
R. Betti	Kinetic Effects on the Resistive Wall Mode	20+10
J. Finn	New Results on Resistive Wall Instabilities	20+10
	*** * * Break * * ***	
M. Okabayashi	MHD Instabilities in PBX-M with a Nearby Conducting Shell	20+10
T. Ivers	Wall Stabilization Experiments in HBT-EP	20+10
G. Navratil	DIII–D Wall Stabilization Experiments	20+10

APPENDIX B
MHD WORKSHOP AGENDA (Continued)

Error Fields and Locked Modes: Theory and Experiment		1:30 p.m.
R. Fitzpatrick	Driven Reconnection in Magnetic Fusion Experiments	40+10
	*** Break ***	
R. La Haye	Experimental Overview of Error Field & Resistive Wall Induced Locked Modes in High Beta Tokamaks	40+10
R. Yoshino	Plasma Rotation & Error Field Instabilities on JT-60U and JFT-2M	40+10
	RECEPTION AND COCKTAIL PARTY	5:45 p.m.

Wednesday, September 13 — Day 3

Effect of q_0 on Plasma Stability		8:30 a.m.
L. Zakharov	Non-Ideal Effects in MHD	30+10
S. Migliuolo	Search for a Beta Threshold for n=m=1 Modes in TFTR Discharges with $q_0 < 1$	20+10
F. Waelbroeck	Gyroscopic Stabilization of the Internal Kink Mode	20+10
	*** Break ***	
W. Park	High Beta Disruption in Tokamaks	20+10
E. Fredrickson	MHD and Disruptions in the Enhanced Reversed Shear Mode	20+10
A. Turnbull	MHD Stability of Simulated ITER Discharges in DIII–D	15+10
Porcelli/Boucher	Sawtooth Model for ITER	15+10
Poster Session #1:		1:30 p.m.
C. Kessel	The Effect of Steady State on ITER Profiles & Stability	
Z. Chang	Observation of grad-P Driven Neoclassical Modes in TFTR	
S. Tokuda	Beta Limit Analysis for ITER Profiles and Shape Effects	
S. Mirnov	On the Way to Phenomenological Model of the ITER Disruption	
T. Jensen	Pressure Driven Equilibrium	
L. Lao	Analysis of High Performance Discharges in DIII–D with Negative Central Shear	
E. Lazarus	Poloidal Mode Number Identification in Finite b Noncircular Cross Section Plasmas	
Poster Session #2:		
M. Phillips	Stability of Rev. Shear Equilibria in TFTR	
L. Charlton	Numerical Simulations of ELM Behavior	
H. Wilson	Neoclassical Theory for Magnetic Islands in a Low Collisionality Tokamak Plasma	
R. Fitzpatrick	Stabilization of the Resistive Wall Mode with a Fake Rotating Shell	
A. Reiman	Statistical Analysis of the DIII–D Disruption Database	
R. Nebel	Two-Fluid Effects on m=1 Instabilities	
L. Sugiyama	Two-Fluid Studies of Tokamak Plasmas	

APPENDIX B
MHD WORKSHOP AGENDA (Continued)

G.T. Hoang	MHD Activity with q(0) > 1 on Tore Supra
I. Semenov	Phenomenology of Major and Minor Disruptions in High Beta DT TFTR Plasmas

Thursday, September 14 — Day 4

Discussion and Summary Sessions — 8:30 a.m.

S. Jardin	Goals of Discussion and Writing Sessions	15 min.
Group #1	Long Pulse Beta Limits	Charis: Gruber/Monticello
Group #2	Locked Modes—Theory and Experiment	Chairs: Yoshino/Hender
Group #3	Resistive Wall Modes—Theory & Experiment	Chairs: Navratil/Bondeson
Group #4	Effects of q_0 > or < 1	Chairs: Fredrickson/Zakharov

Summary Session: — 1:30 p.m.

Reports from the Discussion Groups — 4 x 30 min.

*** * * Break * * ***

Discussion of What These Mean for ITER — Chairs: Perkins/Wesley — 120 min.

*** * * Adjourn at 5:30 * * ***

Friday, September 5 — Day 5

MHD, Disruptions, and Plasma Control Expert Group Meeting — 8:30 a.m.

Possible Topics:

1. Review Status of ITER Design
2. Review MHD R&D List and Compare with Workshop Summary
3. Capabilities and Plans of the Four Parties
4. Follow-up Discussions from Garching Disruption Workshop
5. Plans for Next Meeting

*** * * Break * * ***

APPENDIX C
FINAL ANNOUNCEMENT

APPENDIX C
FINAL ANNOUNCEMENT (Continued)